Technical Peer Review of the Alcator C-Mod 5-Year Proposal
Plasma Science and Fusion Center
Massachusetts Institute of Technology; May 12-13, 2003
Summary Report by Rostom Dagazian

Executive Summary

The Alcator C-Mod 5-Year Proposal submitted to the Office of Fusion Energy Sciences (OFES) by the Massachusetts Institute of Technology (MIT) was peer reviewed on site by a panel of 8 experts representing a wide cross-section of the US and international fusion community. The OFES charge to the panel was to review the proposal on its: a) Relevance of Research, b) Quality of Research, c) Performance of Operations, and d) Costs of Research and Operations.

The overall theme of the Alcator C-Mod Program is "Compact high-performance divertor tokamak research to establish the plasma physics and plasma engineering necessary for a burning plasma tokamak experiment and for attractive fusion reactors." Organization of the program is through a combination of topical science areas and programmatic thrusts. The topical areas relate to the generic plasma science, while the thrusts focus it on integrated fusion objectives crucial to the international program. The two current thrusts of the program are Advanced Tokamak and Burning Plasma Support. The first involves employment of a new Lower Hybrid Current Drive system as the principal means of detailed control of the C-Mod discharge. The latter takes advantage of the high-field/high-pressure capability of the facility and also includes some critical research aimed at resolving performance questions related to next-step fusion experiments. The major strengths of the C-Mod program are its versatile and well diagnosed facility, which is relatively inexpensive to operate, and its strong educational program.

The panel members' findings were submitted as individual reports and a summary of the comments was prepared by Jim Luxon (General Atomics), the panel chair. The review results were very positive for MIT. In the independent reports, the reviewers gave mostly excellent marks to MIT's performance to date and to the five-year proposal. They also supplied valuable comments and suggestions on details relevant to further optimizing the program, manpower needs, interactions of the C-Mod team with others, etc. In what follows, we present some of the conclusions from the review.

I. Introduction

The Plasma Physics and Fusion Center (PSFC) of MIT submitted a Proposal to OFES for a 5-year Cooperative Agreement on the Alcator C-Mod National Facility Operation and Fusion Program research in March of 2003 . The work is to be carried out from November 1, 2003 thru October 30, 2008. The total cost of the proposal is $140,907,000. The technical part of this proposal was originally drafted by the C-Mod team for discussion at the National Tokamak Workshop which took place at General Atomics in

June 2002. The proposal was finalized on the basis of that community discussion. The Princeton Plasma Physics Laboratory (PPPL), MIT's major collaborator on C-Mod, prepared a companion document to describe its role in the program.

OFES selected a panel of eight independent experts to peer review the MIT proposal. The panel members represent a broad spectrum of expertise and included distinguished members of the international fusion community: The panel was chaired by Jim Luxon of General Atomics and also comprised:

D. Hill (LLNL),
D. Post (LANL),
R. Kaita (PPPL),
G. Cava (PAO),
T. Ozeki (JT-60, JAERI, Japan),
F. Leuterer (IPP-Garching, Germany),
D. Batchelor (ORNL).

J. Willis and R. Dagazian participated from OFES.

The detailed charter for the review is shown in Attachment 1. The charge was to review the proposal for: a) Relevance of Research, b) Quality of Research, c) Performance of Operations, and d) Costs of Research and Operations.

The MIT staff made presentations during the first 1.5 days of the review addressing the questions in the charter. In addition, there was an independent PPPL presentation delineating PPPL's plans and issues for the collaboration.

The presentations will be briefly discussed in Section II, and the panel conclusions will be summarized in Section III. The summaries are based on the individual reports received from the members of the Review Panel. The panel members were instructed to consider the topics requested in the charter and to try to use the format of the standard grant peer review questionnaire used by OFES (Attachment 2) .

II. Review Presentations

The agenda for the review is shown in Attachment 1. The Viewgraphs used at these presentations can be accessed through the electronic version of this agenda. The MIT presentations were organized to describe the current status of and 5-year plans for the Advanced Tokamak (AT) and the Burning Plasma Support research thrusts. Detailed presentations of the various research subtopics followed including the special presentation by PPPL.

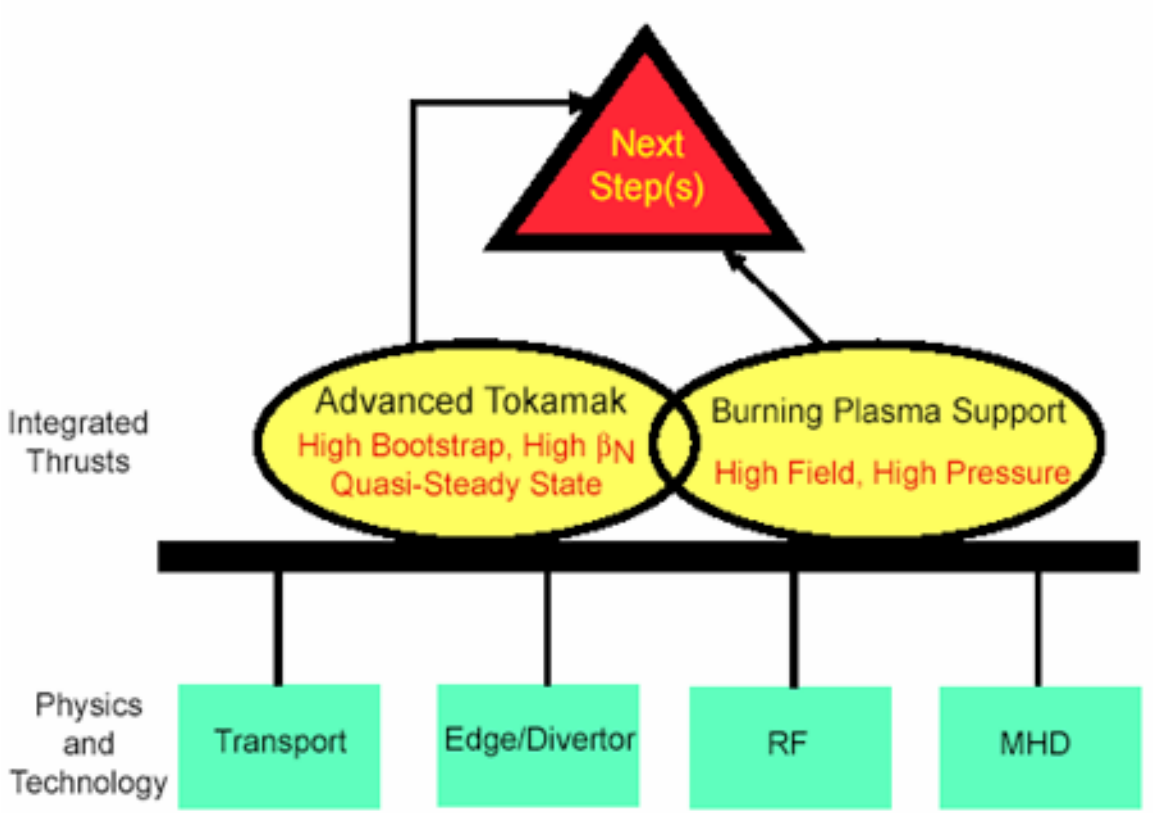
Professor Miklos Porkolab, PSFC director, opened the presentation session by presenting the mission and a summary of the activities of the PSFC.

PSFC's mission is the advancement of plasma science, its applications, and the education of the next generation of scientists and engineers. Its many and varied activities include support for approximately 50 graduate students per year.

Earl Marmar, C-Mod Principal Investigator, continued by giving an overall accounting of the successes of the program over the current grant period (coming to an end) and describing proposed plans for the next five year period.

The overall theme of the Alcator Program is "Compact high-performance divertor tokamak research to establish the plasma physics and plasma engineering necessary for a burning plasma tokamak experiment and for attractive fusion reactors." Organization of the program is through a combination of topical science areas and programmatic thrusts. The topics relate to the generic plasma science, while the thrusts focus it on integrated fusion objectives crucial to the international program. The two current thrusts of the program are Advanced Tokamak and Burning Plasma Support. As already mentioned above, the first involves employment of a new Lower Hybrid Current Drive system as the principal means of detailed control of the C-Mod discharge. The latter takes advantage of the high-field high-pressure capability of the facility and also includes some critical research aimed at resolving performance questions related to next-step fusion experiments. The major strengths of the C-Mod program are its versatile and well diagnosed facility, relatively low cost operation, and a strong educational program.

The Alcator C-Mod program's two major thrusts supported by fundamental topical science are directed at support of planned next steps in Fusion research as illustrated below:



Numerous C-Mod program achievements include observations of strong core rotation with no applied external torque, pointing out the importance of midplane recycling in tokamaks, cross-field transport in the scrape-off layer (SOL) and its correlation with bursty transport events, relation of the tokamak density limit to cross-field transport and turbulence, identification of the mode-converted Ion Cyclotron wave (ICW), measurement and scaling of halo currents during vertical displacement events (VDEs), discovery of Internal Thermal Barrier formation and control by on- and off-axis heating by radio frequency waves, extensions of the ITER data base to new parameter regimes, and last but not least: proof of suitability of high-Z walls (Mo) for high power divertor operation.

The Integrated Program Planning Activity (IPPA) has developed four high level goals for MFE, endorsed by the Fusion Energy Sciences Advisory Committee (FESAC):

1) Advance fundamental understanding of plasma, and enhance predictive capabilities , through comparison of well-diagnosed experiments, theory and simulation;
2) Resolve outstanding issues and establish reduced –cost paths to more attractive fusion energy systems, by investigating a broad range of innovative magnetic confinement configurations;
3) Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements, and participate in a burning plasma experiment;

4) Develop enabling technologies to advance fusion science, pursue innovative technologies and materials to improve the vision for fusion energy, and apply systems analysis tools to optimize fusion development.

The Alcator program has contributed to all of the four goals and is planning to continue contributing with the strongest effort going into goals 1 and 3. Goal 1 is addressed by working on plasma core turbulence, high performance plasmas, non-inductive current drive (radio frequency and LH microwaves), active MHD diagnostics, scrape-off layer physics and divertor physics. Goal 3 is addressed by work on quasi-steady-state advanced tokamak work (centered around the new C-Mod LH microwave current drive system) and Burning Plasma support with integrated high-field/ high-density performance.

In the extensive presentations on particular topics, the following propositions stood out:

In the Advanced Tokamak target the integrated goal will be achievement of normalized beta β_N equal to 3, confinement improvement factor H approximately equal to 2.5, bootstrap current fraction greater than 70%, non-inductively driven total current of 0.85MA and pulse duration equal to at least one current redistribution time. Microwave current drive at the Lower Hybrid (LH) range of frequencies and radio frequency (ICRF) power application at high densities will be C-Mod's main tools for achieving this kind of performance relevant to ITER and to the Component Test Facility (CTF) and fusion power plant DEMO. The C-Mod program will be a critical part of the US effort in configuration optimization, required early in the fusion development path.

In the Burning Plasma thrust, the goal is to study phenomena and plasma regimes prototypical of proposed next step experiments (ITER, FIRE, and IGNITOR) and resolve potential physical obstacles to ignition and burning such as edge relaxation mechanisms, disruptions, neoclassical tearing modes, and high power operation with acceptable divertor heat loads

The presentations gave substantial details on physics issues and rationale for the need of further facility upgrades to accomplish the physics goals (see vugraphs).

Jim Irby described many improvements performed on the C-Mod facility in the recent past including changes to the C-Mod inner divertor, rework of the TF magnet coils, completion of the LH project in collaboration with PPPL, modifications in the Cylinder and the Cryostat resulting in improved tangential diagnostic access and a 50% increase of the number of discharges per day, the fabrication, installation and operation of non-axisymmetric passive coils for locked mode control etc.

Upgrade plans include the following:

An additional LH coupling launcher.
A new 4-strap ICRF antenna.
Modifications to the outer divertor and addition of a cryopump.

Active stabilization coils.
ICRF Power Supply and RF Cavity upgrades
A new long pulse Diagnostic Neutral Beam (DNB)

Many upgrades to existing diagnostic systems and many new diagnostics are also being planned. These will focus on improved understanding of ITB discharges and of turbulence.

Tables indicating the most important upgrades (including their cost and year in which they are scheduled) are provided below:

FACILITY UPGRADES

Item	Hardware Cost ($k)
Cryopump (05)	420
Outer Divertor Upgrade (power handling) (06)	350
Vessel Upgrade (horizontal ports) (06)	300
Digital Plasma Control System (06)	90
Control Coil Power Supply Upgrades (05)	60
Active Stabilization (08)	975

Blue: Delayed
Red: Deferred
} on Guidance Budgets

LOWER HYBRID SYSTEM UPGRADES (FY04-05)

- Add 2'nd launcher, 4 additional klystrons (+1 MW)

Item	Hardware Cost ($k)
Coupling Launcher	1850
Data Acquisition, Instrumentation and Control	170
Protection, Power Meters, Conversion Components	220
High Power Transmission Components	365
Klystron Cart	125
Spare Klystrons (2)	900

ICRF UPGRADES (FY05-07)

Item	Hardware Cost ($k)
New 4-strap Antenna (05)	400
Real-Time Matching Systems (05)	750
Power Supply Upgrades (07)	1780
Cavity Conversions (tunable from fixed) (07)	700

CORE DIAGNOSTICS

Item	Hardware Cost ($k)
Long Pulse DNB (04)	600
Polarimeter/Interferometer (05)	570
PCI (second view) (07)	550
Imaging X-Ray Crystal Spectrometer (06)	300
Heterodyne ECE upgrade (07)	300
Laser Scattering Fluctuation Diagnostic (06)	250
MSE (second view) (05)	240
Non-Thermal ECE (fast electrons) (06)	200
PCI upgrade (electron scale) (06)	120
MSE resolution, CXRS detector, Active MHD Up., Core Thomson resolution, HIREX electronics	300

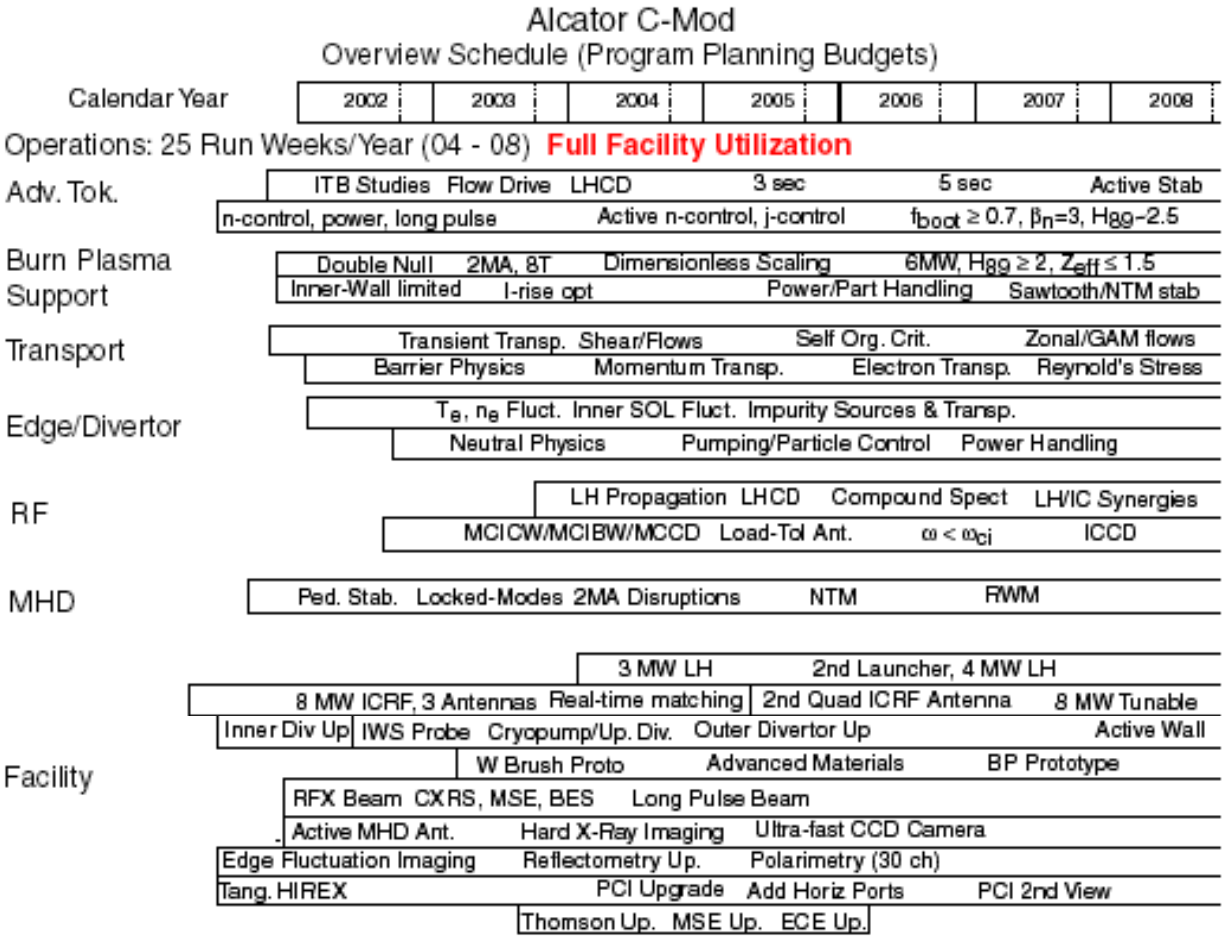
EDGE/ SCRAPE-OFF LAYER DIAGNOSTICS

Item	Hardware Cost ($k)
Laser Induced Fluorescence (07)	500
Lithium Beam Polarimeter (06)	200
Edge ECE (08)	200
SOL Thomson Scattering upgrade (05)	120
Probe upgrades (04-06)	160
Divertor IR Cameras (05, 07)	100
Neutral Tomography Imaging (06)	100
Flow Imaging (05)	75
Edge Fluctuation Imaging upgrade (05)	70
Deposition Monitors, LH Grill density, Dust diag.	160

In addition, many upgrades are planned for the C-Mod DATA SYSTEM including mass storage improvements (currently data require 1-2 Tbytes of new capacity per year), new digitizers, and LAN upgrades and switching to a Linux configuration by the end of CY 2004.

It is important to note that, in the past, MIT has provided significant institutional support for C-Mod projects. The LH project alone has benefited from $1.5M contributed by MIT for various Nabisco Lab improvements. MIT has also contributed $180k to renovate/enlarge the C-Mod control room and has approved plans to air condition the power supply room ($310k).

The C-Mod upgrades are very moderate in cost due to the small size of the facility. A tentative SCHEDULE FOR OPERATIONS and various C-Mod activities is summarized in the table below:



Finally, in a very nice presentation, Environment Health and Safety (EHS) considerations were addressed by C. Fiore. The notable observation here is that C-Mod is helping the MIT overall program to reshape its approach to EHS.

III. Summary of Panel Deliberations and Responses

Overall, the review was very constructive and helpful to the 5-year MIT plans. In the independently submitted reports, the reviewers gave MIT's performance to date and the five-year proposal mostly excellent marks. They also supplied valuable comments and suggestions on details relevant to further optimizing the program, manpower needs, interactions of the C-Mod team with others, etc. Some of the salient conclusions from the review are as follows:

The C-Mod proposal addresses important issues over the full breadth of plasma science and fusion energy science. It has important foci on the advanced tokamak and burning plasma issues, but nevertheless contains a program that addresses all the traditional areas of stability, transport, boundary and wave-particle interaction. RF heating and current

drive and plasma-boundary interaction are two important areas where C-Mod is and will continue contributing.

The proposed research has significant unique features in the U. S. and world programs. This includes the use of high toroidal field (compensating for the smaller size of the plasma), and the use of RF exclusively, focusing on ICRF and LH waves, to heat and drive current in the plasma. The ability to run at high densities, with $T_e \sim T_i$, and with pulse lengths of several current relaxation times will make these results particularly useful. Successful application of these techniques will result in significant contributions to the database for a burning plasma device. The use of heavy metals on the first wall surfaces to manage heat loads is unique in the program and is the front-running technology for use in reactor applications. This approach has led to original work and to unique understanding and solutions in the past and will likely continue to be productive in the future.

Given the innovative work done in the C-Mod program in the past, the tools already available, and the tools proposed, it is likely that the C-Mod will make significant fundamental advances during the period of work proposed in this proposal.

The C-Mod group, led by the principle investigators, has an excellent reputation in the fusion community for high quality research, has published extensively in refereed journals, and participates actively in the many fusion meetings and forums.

The research facilities at MIT present an excellent environment in which to carry out the proposed research. Not only are the facilities appropriate, but the on-campus site provides a setting that cultivates research. It also provides access to both a ready source of graduate students and to experts in related areas of research.

The proposed budget is just adequate to carry out the proposed program. The program must have adequate funds to provide the equipment needed to carry out the proposed research. It is especially important that they acquire the proposed levels of RF power along with the appropriate launchers if the current drive and heating programs are to realize their potential. There is a strong argument for running the facility at the level of 25 weeks per year, but not at the expense of providing the hardware to advance the research effort.

The present staff is just barely adequate in size, and they will find carrying out this research program demanding. Additional staff, focused particularly on relating the experiments to theory, would help considerably. The group has made good use of collaborative research in both their experimental program and in the analysis and understanding of their results. However, they could better use collaborative research programs, particularly with other institution staff assigned on-site to augment the in-house capabilities. Further collaboration with theorists and modelers is strongly encouraged.

Special kudos were offered by the panel members on MIT's success with the MDSplus plasma data control system which was originated at C-Mod and is now universally used within the Fusion community.

In the edge and divertor area, C-Mod's contributions have been outstanding with significant impact on the international boundary physics community and earning a clear first place in the US.

ES&H issues are being adequately addressed and a walk-through of the C-Mod facility indicated that the facility is in good working order and that C-Mod personnel are committed to safety.

The C-Mod group is also unique in having a large graduate education program associated with it. This results in a regular stream of high quality PhD and masters graduates from the program. These students often take positions in the fusion community and will help provide the future generation to staff a burning plasma device. The strong involvement of students also benefits the C-Mod program by providing a base of new and innovative ideas.

A) Point by Point Response to the Review Charter:

1. *Assess the **relevance** of the proposed 5-year fusion **research** with respect to the goals of the U.S. fusion program as outlined in the Integrated Program Planning Activity, and in particular to the Burning Plasma Physics related studies in response to the recent U.S. decision to join the ITER negotiations and continuing interest in the FIRE and IGNITOR projects. Is the research likely to accomplish its stated objectives? How well is the research coordinated with other national and international fusion research activities?*

The Alcator C-Mod program is clearly addressing some of the top issues identified by FESAC and IPPA. Hitherto work has had and future plans will continue to have impact on future Next Step Experiments in the Fusion program. The proposed research objectives will be attained if adequate funding is provided.

Improvements in the tokamak concept will undoubtedly result from the C-Mod AT program. The Burning Plasma Physics thrust is addressing key problems in the design of ITER, FIRE and IGNITOR. Through its strong emphasis on edge physics, significant contributions are expected in the atomic physics and materials science areas. Important spin-offs could include contributions to the fields of space and astrophysics.

The research is well coordinated with other national and International efforts. Notable are the dimensionless scaling ("wind-tunnel-like") experiments in collaboration with DIII-D, JET and ASDEX-UG. However, there is always room for further collaboration and notably with theorists and modelers.

2. *Assess the **quality** of the ongoing and planned **research**. Does the research proposed address science at the forefront of the field? Does the ongoing and planned research maintain a U. S. leadership position in key areas of fusion*

research? Does the proposed work provide for an adequate set of diagnostics, other necessary facility upgrades, interactions with theory and modeling, and collaborations involving a broad group of domestic and international users?

The C-Mod group is a small but very distinguished group in the world fusion program. The group includes several "stars" with original and well recognized contributions to the program. Their performance record is outstanding. The proposed plan keeps up with this record.

C-Mod's operation in high density regimes with approximately equilibrated electron and ion temperatures, its metal walls, and the high heat fluxes are all features prototypical of Next Step devices. The proposed program is expected to make good use of these features to address questions pertinent to the design and operation of these machines.

C-Mod has developed a comprehensive set of diagnostics which in recent years has been augmented by the addition of a diagnostic neutral beam (DNB) which supports some very important systems like the MSE, BES, CXRS. A new DNB with optimized specs is on order and it is expected to further help the existing diagnostics. Other diagnostics planned and under development will focus on understanding internal transport barriers (ITB's) and turbulence. Understanding the underlying physics of these topics is expected to provide new insights into the operation and design of Next Steps.

3. *Assess the current level of quality of **performance** of facility **operations**. Are milestones being met? Are planned operating, maintenance, repair and upgrade schedules being achieved? Are environment, safety, health and quality assurance matters being addressed appropriately? Assess the program's governance practices and the performance of the direct program management as well as the support provided from the host institution.*

After repairs following the setbacks of an alternator failure in FY97 and the toroidal field coil fault repaired in FY98, C-Mod has operated with high reliability to the present day. Milestones have generally been met although completion of the Lower Hybrid (LH) project was slightly behind schedule. The 97/98 repairs seem to have been very effective and they have been accomplished with little extra cost to DOE. In fact, MIT's insurance paid for the alternator repair.

MIT has provided and continues to provide important institutional and infrastructure support for the C-Mod program. The C-Mod/PSFC Environment Health and Safety (EHS) program is now providing valuable input into the MIT overall EHS system and is subject to regulatory oversight from a number of agencies (OSHA, EPA. DOT, Massachusetts DOL and DEP) and the Cambridge Fire department. Improvement on the minor lost time accident rate is still desirable.

The research effort is well organized under 4 Topical Science Areas and the two cross-cutting thrusts (AT and BP). An experimental Program Committee, comprising representatives of major collaborating institutions, coordinates the research program.
The panel generally made positive comments on MIT's governance practices which have resulted in a well run operation in the past and thus are expected to help the program in the future.

4. *Assess the reasonableness of the proposed **costs** for fusion **research** and **operations.** The cost review should be done at a summary type level, examining major items and projections from ongoing operational experience.*

The proposed budget was evaluated by the cost and schedule expert members of the panel to be reasonable and offer excellent value for the money. The evolution of the C-Mod program requires completion of key hardware systems and diagnostics and is key to achieving results fully valuable to the community. The C-Mod team has an appropriate understanding of the relative priorities involved to render the program fully successful.

Attachment 1

Alcator C-Mod 5 Year Program Plan Review

May 13 - 14, 2003
NW17-218
Agenda

Tuesday, May 13, 2003

8:00	Executive Session	
8:30	Welcome	M. Porkolab
8:40	Introduction	I. Hutchinson
8:50	Charge	J. Willis/R. Dagazian
9:00	Program Overview	E. Marmar
10:15	Break	
10:30	Advanced Tokamak Program	A. Hubbard
11:20	Burning Plasma Support Program	S. Wolfe
12:10	Lunch (on-site)	
1:00	Facility Tour	
1:30	Transport	M. Greenwald
2:15	RF	S. Wukitch
3:00	Break	

3:15	Divertor and Edge Physics	B. Lipschultz
4:00	MHD and Stability Research	R. Granetz
4:30	Executive Session	

Wednesday, May 14, 2003

8:00	Executive Session	
8:30	PPPL Collaboration	G. Schilling
9:00	Operations and Facilities	J. Irby
10:15	Safety	C. Fiore
10:30	Break	
10:45	Program Planning	S. Wolfe
11:15	Budget and Schedule	E. Marmar
12:00	Executive Session (lunch on-site)	
4:00	Feedback from Panel	
5:00	Adjourn	

Attachment 2

To: Distribution

Subject: MIT Proposal for a 5-Year Cooperative Agreement on the Alcator C-Mod National Facility Operation and Fusion Program Research

Thank you for agreeing to participate in a review of a proposal from the Massachusetts Institute of Technology (MIT) to continue the operation of Alcator C-Mod for another 5 years, beginning November 1, 2003. The review will be held at the Plasma Science and Fusion Center at MIT, May 13-14, 2003.

The Alcator C-Mod National Fusion Program involves one of the three major Magnetic Fusion Energy facilities in the United States, and it includes Princeton Plasma Physics Laboratory (PPPL) as a major collaborator, and several universities and foreign laboratories in addition to MIT. The 5-year proposal was prepared by MIT and it describes the totality of the Alcator C-Mod program. PPPL has prepared an accompanying document describing PPPL's plans for collaboration.

We would like you to perform the following assessments:

1. Assess the **relevance** of the proposed 5-year fusion **research** effort with respect to the goals of the United States fusion program as

outlined in the Integrated Program Planning Activity, and in particular to the Burning Plasma Physics related studies in response to the recent United States decision to join the ITER negotiations and continuing interest in the FIRE and Ignitor projects. Is the research likely to accomplish its stated objectives? How well is the research coordinated with other national and international fusion research activities?

2. Assess the **quality** of the ongoing and planned **research**. Does the research proposed address science at the forefront of the field? Does the ongoing and planned research maintain a United States leadership position in key areas of fusion research? Does the proposed work provide for an adequate set of diagnostics, other necessary facility upgrades, interactions with theory and modeling, and collaborations involving a broad group of domestic and international users?

3. Assess the current level of quality of **performance** of facility **operations**. Are milestones being met? Are planned operating, maintenance, repair, and upgrade schedules being achieved? Are environment, safety, health, and quality assurance matters being addressed appropriately? Assess the program's governance practices and the performance of the direct program management as well as the support provided from the host institution.

4. Assess the reasonableness of the proposed **costs** for fusion **research** and **operations.** The cost review should be done at a summary type level, examining major items and projections from ongoing operational experience.

As indicated above, these programs are carried out by collaborative national research teams. The proposed research plan from the national team should be reviewed for the relevance and quality of the proposed research and the adequacy of the proposed equipment to carry out that research. You are also welcome to comment on the relevance and quality of the research carried out by PPPL, described in the companion document.

Please feel free to comment on any other issue relevant to the proposal.

Jim Luxon has kindly agreed to chair the panel. MIT will provide you with copies of the proposal and any other material helpful for the review. I would like to receive individual written comments on your findings, in a brief draft outline at the end of the review, and a written report by June 6, 2003. The Panel Chair will organize and run the meeting. The chair will submit a summary of the recommendations. He will provide a brief

oral summary and his overall assessment of the review.

John W. Willis
Director, Research Division
Office of Fusion Energy Sciences
Office of Science